Turning Concepts into Reality

Distributed Solar-Thermal Combined Heat and Power

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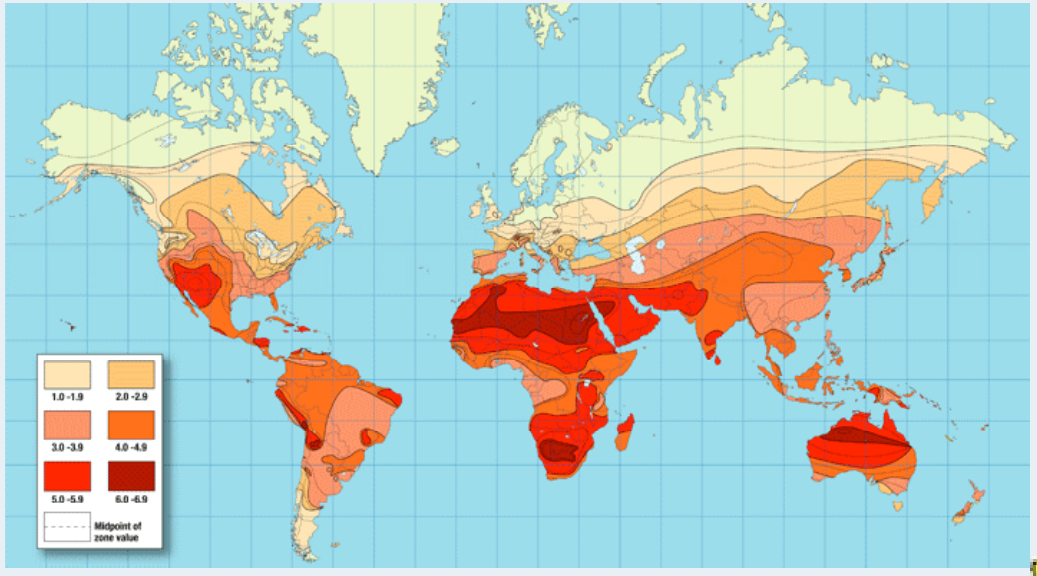
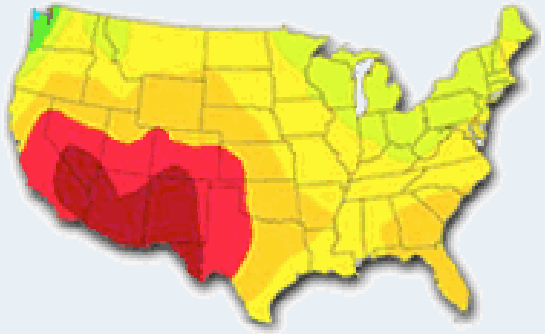
LBL EETD

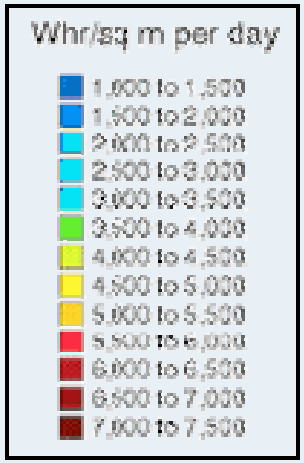
Outline

- Why Solar-thermal?
- Technology
  - Low-temp heat-engines (Stirling, Rankine)
  - Thermodynamic analysis of system
  - Non-imaging concentrating parabolic collectors
- System Analysis
  - Costs
  - Demand scenarios

Why Solar in California?







Solar resource for a flat-plate collector

Why Solar Thermal? Flexibility

- Combined Heat and Power

  w/ thermal storage at moderate temps (<500K)

  – on-demand electrical with low-temp heat engine generator

  – domestic hot water

  – space heating

  – refrigeration, cooking, etc.

- Distributed or centralized power

Added Value of Heat

- Proximity to residence or business (distributed system)
- "Waste" heat can be more than 4 times electricity
- Displaced natural gas is $8.00/MBtu, or about 1.87cents/kWh with 85% heating efficiency.
- Added value of heat between 2 and 7 cents/kWh

Why Solar-Thermal? Storage.

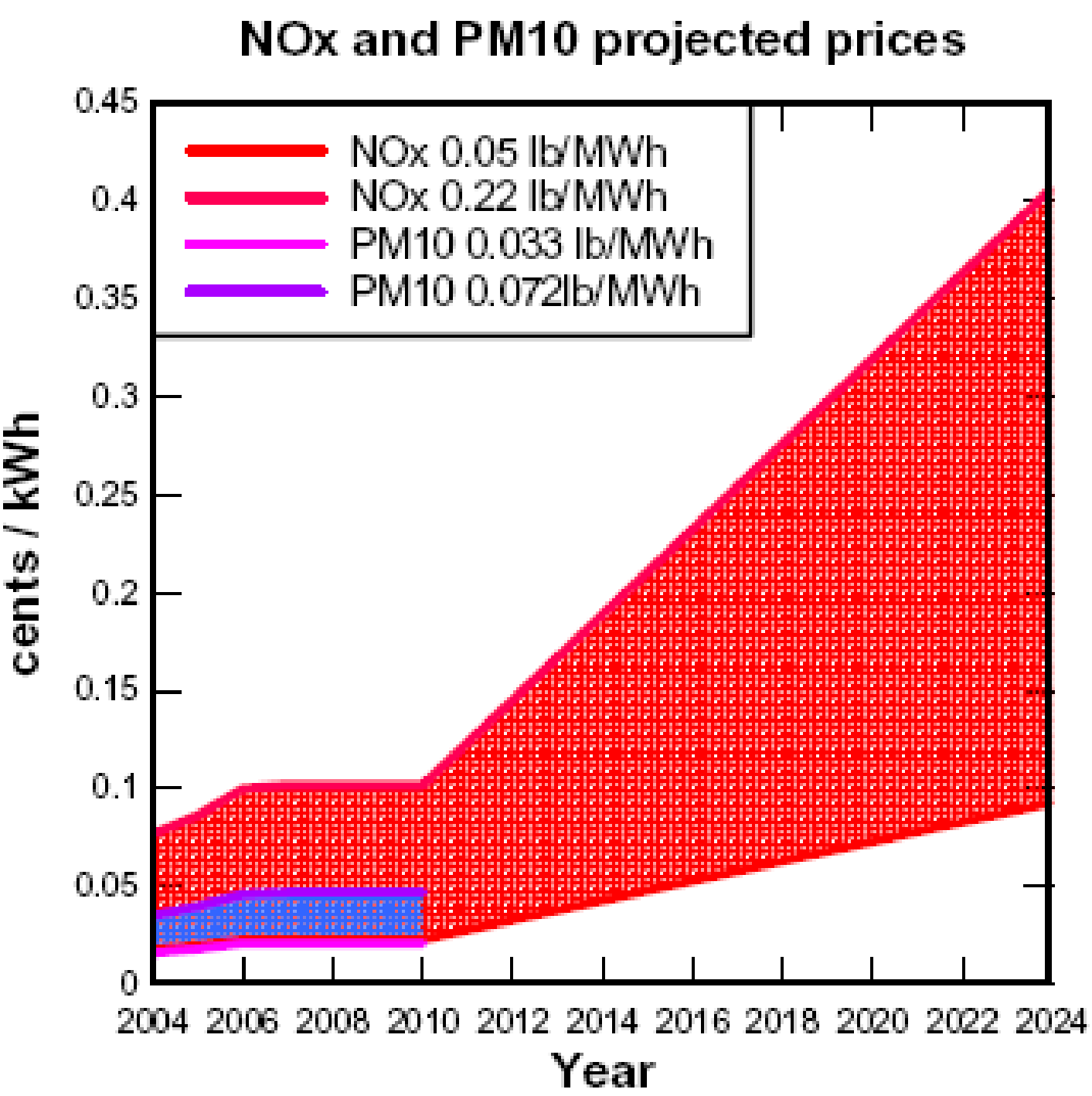
- Electrical storage
  - expensive batteries/capacitors
  - small capacity
- Thermal storage
  - diurnal cycles easily overcome
  - seasonal storage possible in many locations
  - cost effective

Why Solar-Thermal? Cost.

- Small scale CHP systems competing at retail prices for electricity/heat
  - Low capital cost: ~$5/peak Watt Installed
  - Cheap distributed electric power: ~$0.30/kWh
- Peaking Capacity
  - 65% capacity to replace peak power plants (15-30 ¢/kWh)
  - Solar is 50% undervalued! (Borenstein)
- Fuel Hedge
  - Price of natural gas is historically very volatile (& increasing)

Added Value of Solar

- Emissions Offset — Borenstein, 2005
  - NOx – currently regulated ($3.50/lb -> $20/lb in 20 yrs??)
  - PM10 – currently regulated ($4.90/lb -> $20/lb in 20 yrs??)
  - Carbon – likely to be regulated in the future ($30/ton -> $65/ton?)
- Health Benefits
- Greenhouse Gas Abatement
  - Need 70% emissions reduction by 2030 to maintain less than 1 degree Global Warming (Hansen, 2006)


NOx and PM10 projected prices
NOx 0.05 lb/MWh
NOx 0.22 lb/MWh
PM10 0.033 lb/MWh
PM10 0.072lb/MWh
cents / kWh
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2004 2006 2008 2010 2012 2014 2016 2018 2020 2022 2024
Year

Parabolic Trough

Parabolic Dish

Solar Tower

To easily scale to rooftop:

Lower concentration

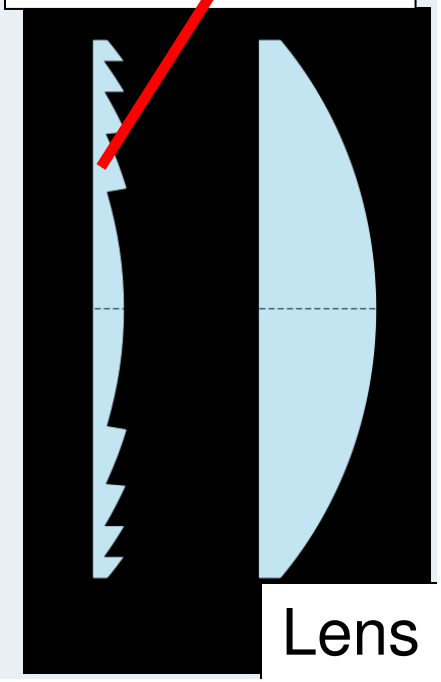
Stationary, building integrated collectors

Luz

SES

Barstow

Fresnel Lens



Lens

SolFocus

Distributed Generation

Turning Concepts into Reality

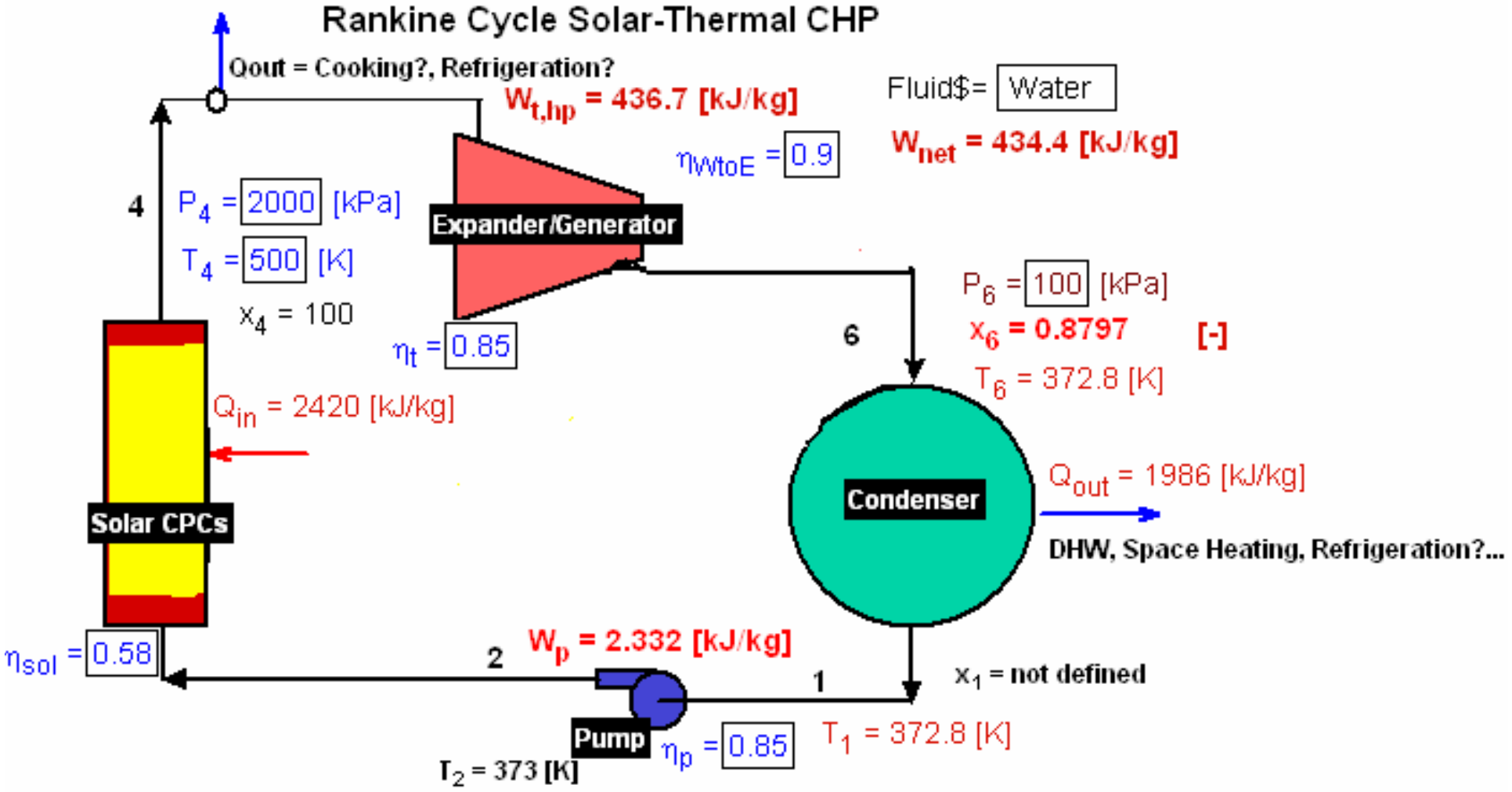
Dedicated system for residences or businesses

Compete with *retail* rather than *wholesale prices*
kWh: 11¢, 33¢ (peak) 5¢, 16¢ (peak)

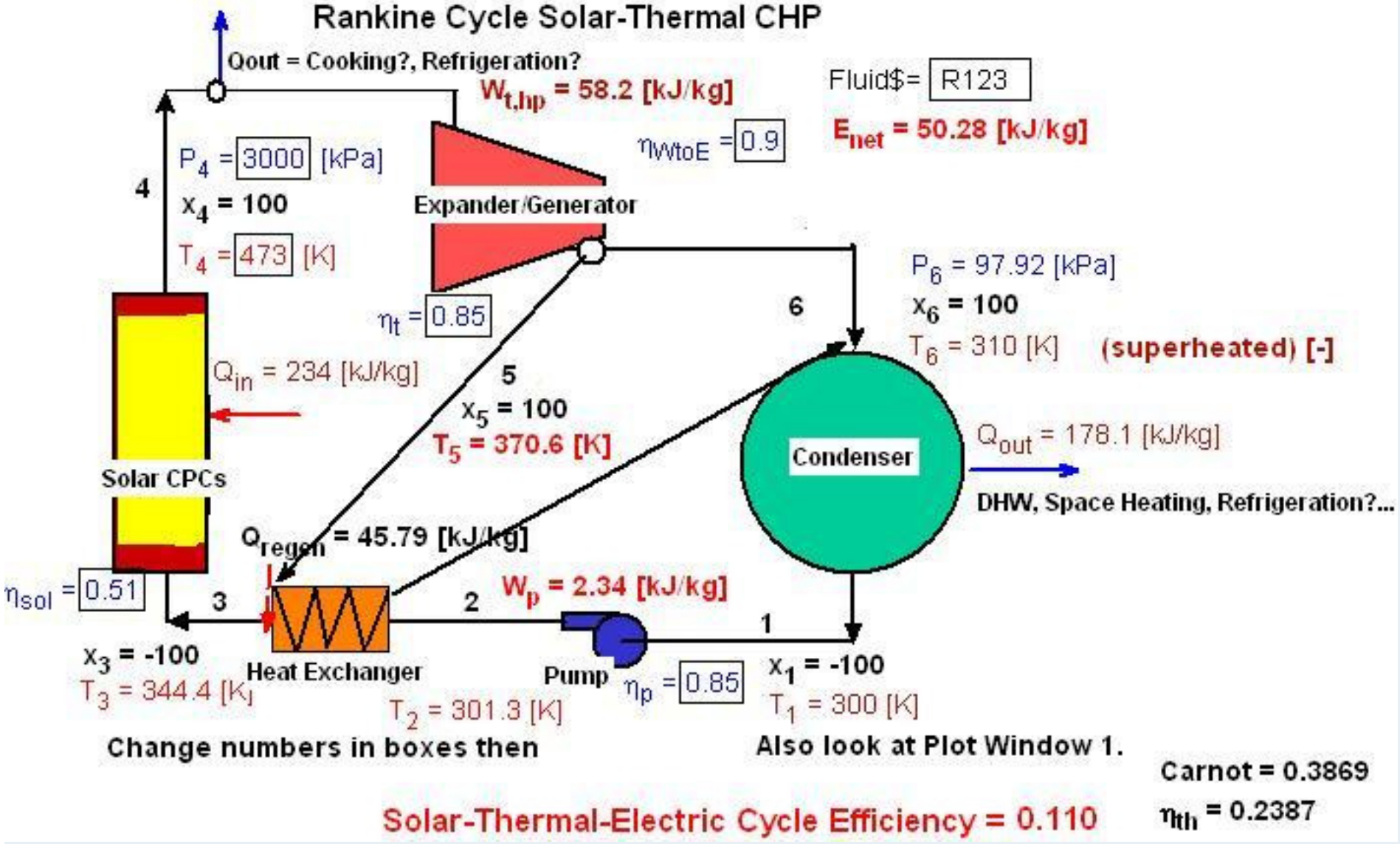
Cost CSP:
30 ¢/kWh

Cost conventional utilities:
33 ¢/kWh (with added value)

Water/EtOH System Diagram



R123 System Diagram



Working Fluids

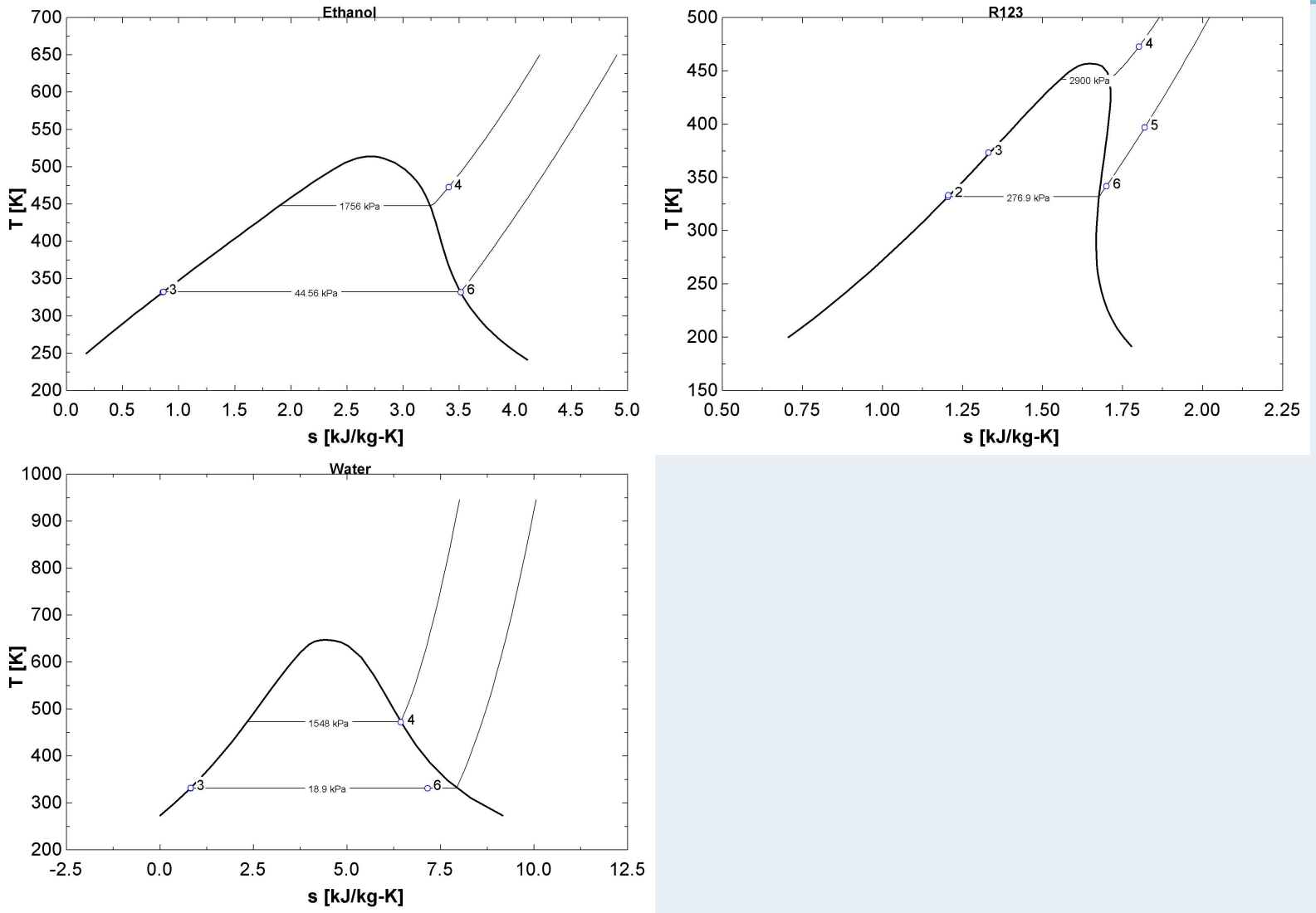


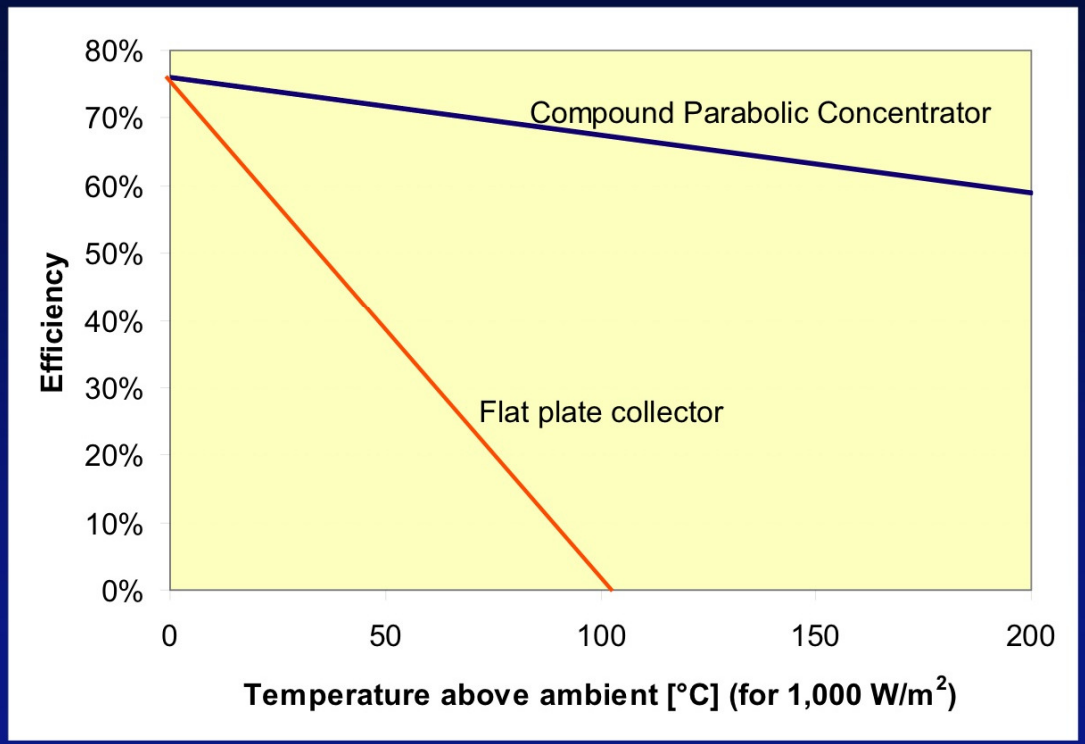
Figure L. Modeled Rankine cycles with Ethanol, R123, and Water

Solar-Thermal System: The Expander

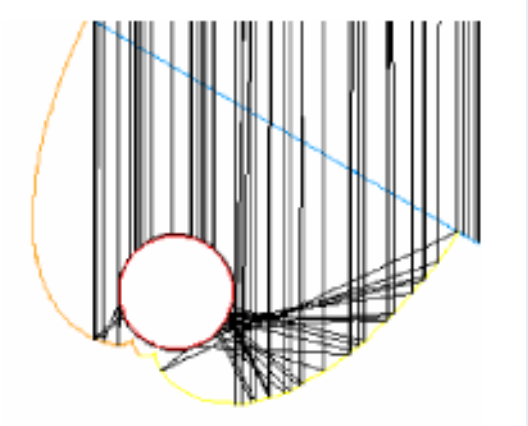
- Water and Ethanol
  - Environmentally preferable
  - High pressure ratio expanders needed for efficient electrical generation
  - Wet-expansion for water could be problematic
- Refrigerant (R123)
  - Good properties for rankine cycles including expansion pressure ratio
  - More complicated with additional heat exchanger
- Expander possibilities include piston, turbo expander, Tesla turbine, impulse turbine, Lysholm screws, Wankels, other rotary lobe expanders, etc.

Compound Parabolic Collector

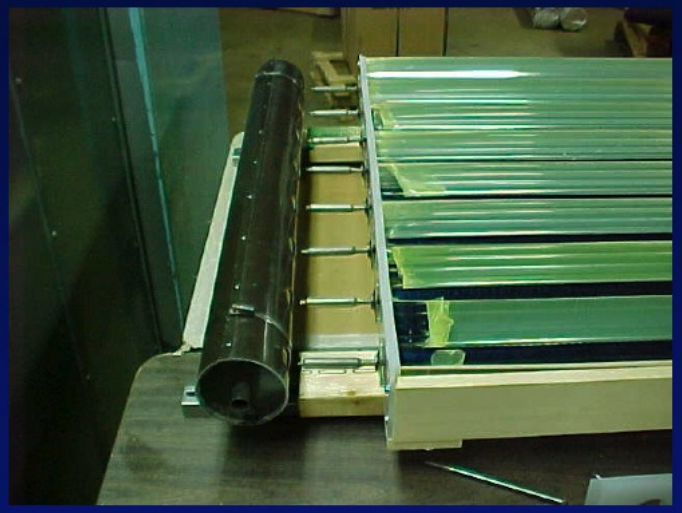
Flat plate collectors are limited to temperatures below 100°C

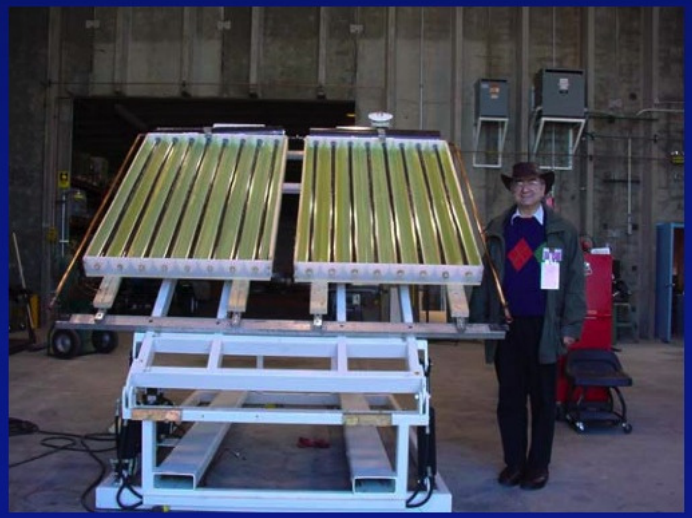


Non-imaging optics



Existing Compound Parabolic Concentrator (CPC) Technology





System Capital Costs

- **Installed Cost $26,794**
- **Cost/kWh $0.31**
- **Cost/peak W $4.96**
- Divided system into panels, bulk of system
- Used cost of materials for panels, retail cost of microCHP system for remainder, 50% install cost
- 15 year lifetime

Winston Series CPC, 18 panels			
components	weight (kg)	$/kg	cost ($)
housing: extruted Al	5.00	6.1	549.00
back plate: Al Sheet .5 mm	3.01	2.86	154.99
insulation: polyurethane foam	0.05	1	0.90
reflector: Ag coated Al	7.00	6.1	768.60
flow tubes: Cu	22.36	6.82	2745.39
cover plate: glass	19.13	1.87	644.06
total			**4863**
Climate energy micro-CHP			
manufacturecd cost			**13,000**
Installed Cost ($)			**26,794**
$/kWhr			**0.31**
$/W			**4.96**

Climate Energy Micro-CHP

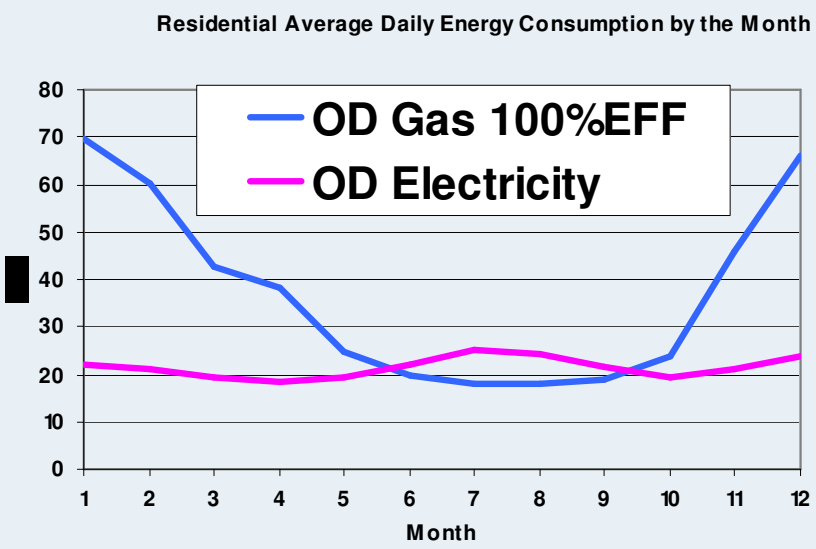
System Analysis Scenarios

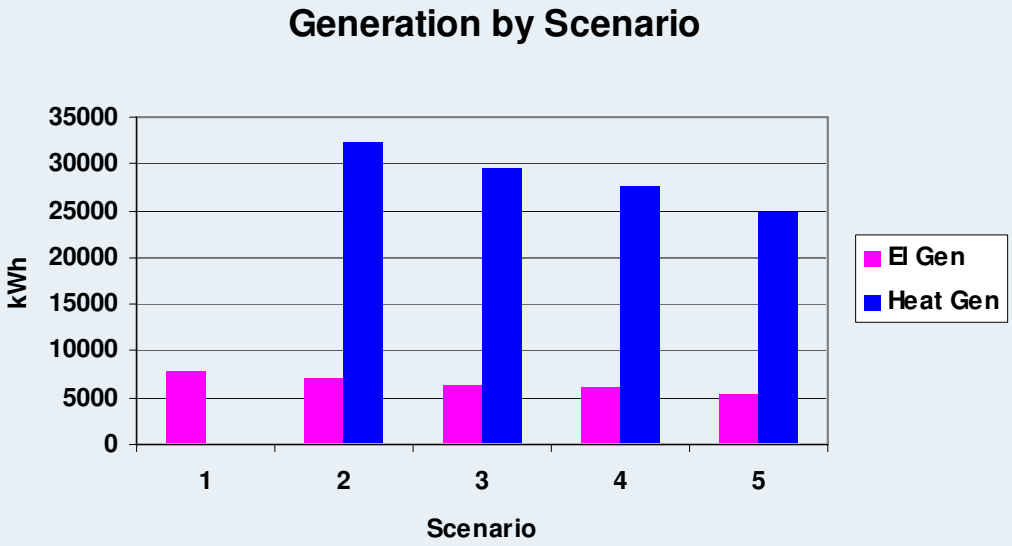
Turning Concepts into Reality

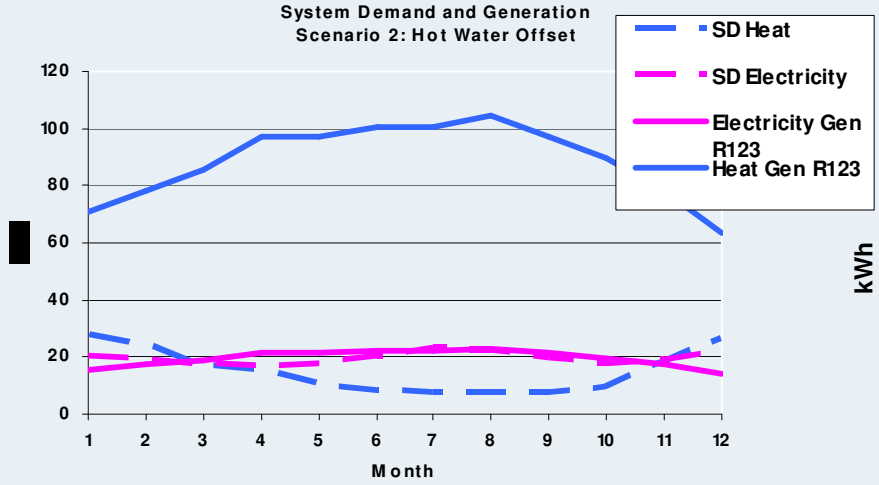
Scenario	Description
1	Electricity only
2	Electricity + DHW
3	Electricity + DHW + A/C
4	Electricity + DHW + Space heating
5	Electricity + DHW + Sp Heat + A/C

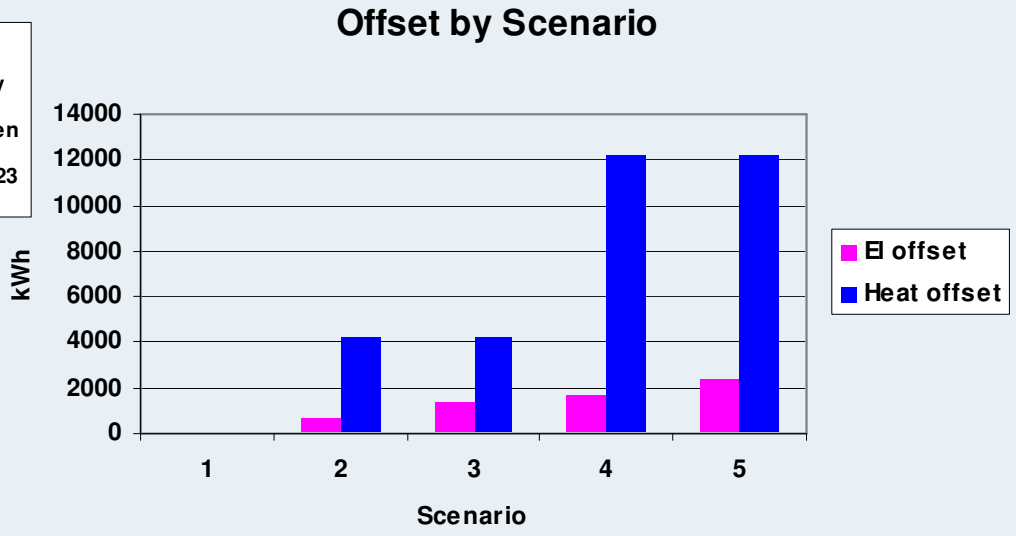
Household Energy Demands

Turning Concepts into Reality









Scenario Results

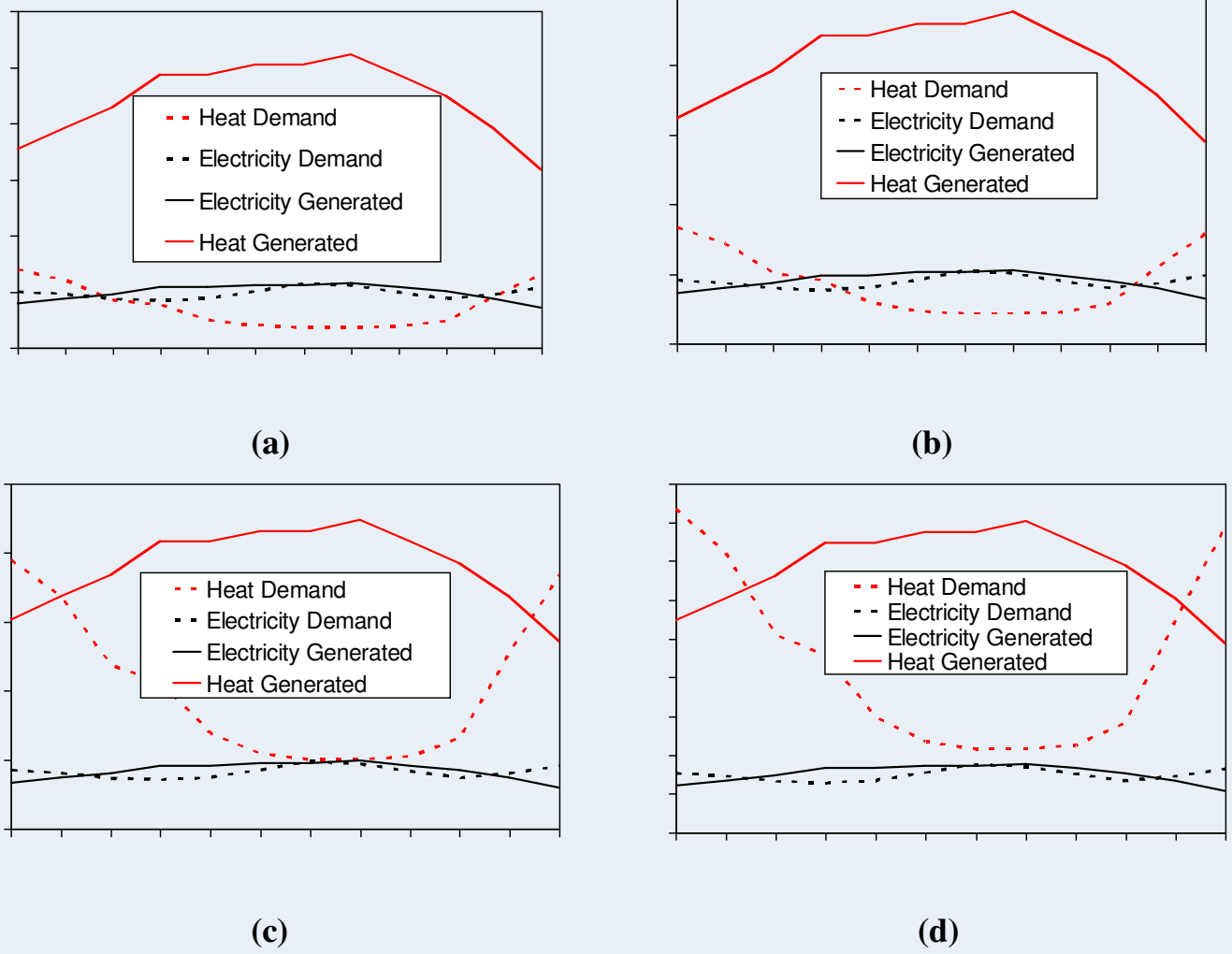


Figure 2. Average California daily demand compared with the R123 solar-thermal systemÕs expected output of electricity and (a) hot water (b) hot water and air-conditioning (c) hot water and space-heating (d) hot water, air-conditioning, and spac e heating.

Scenario Results

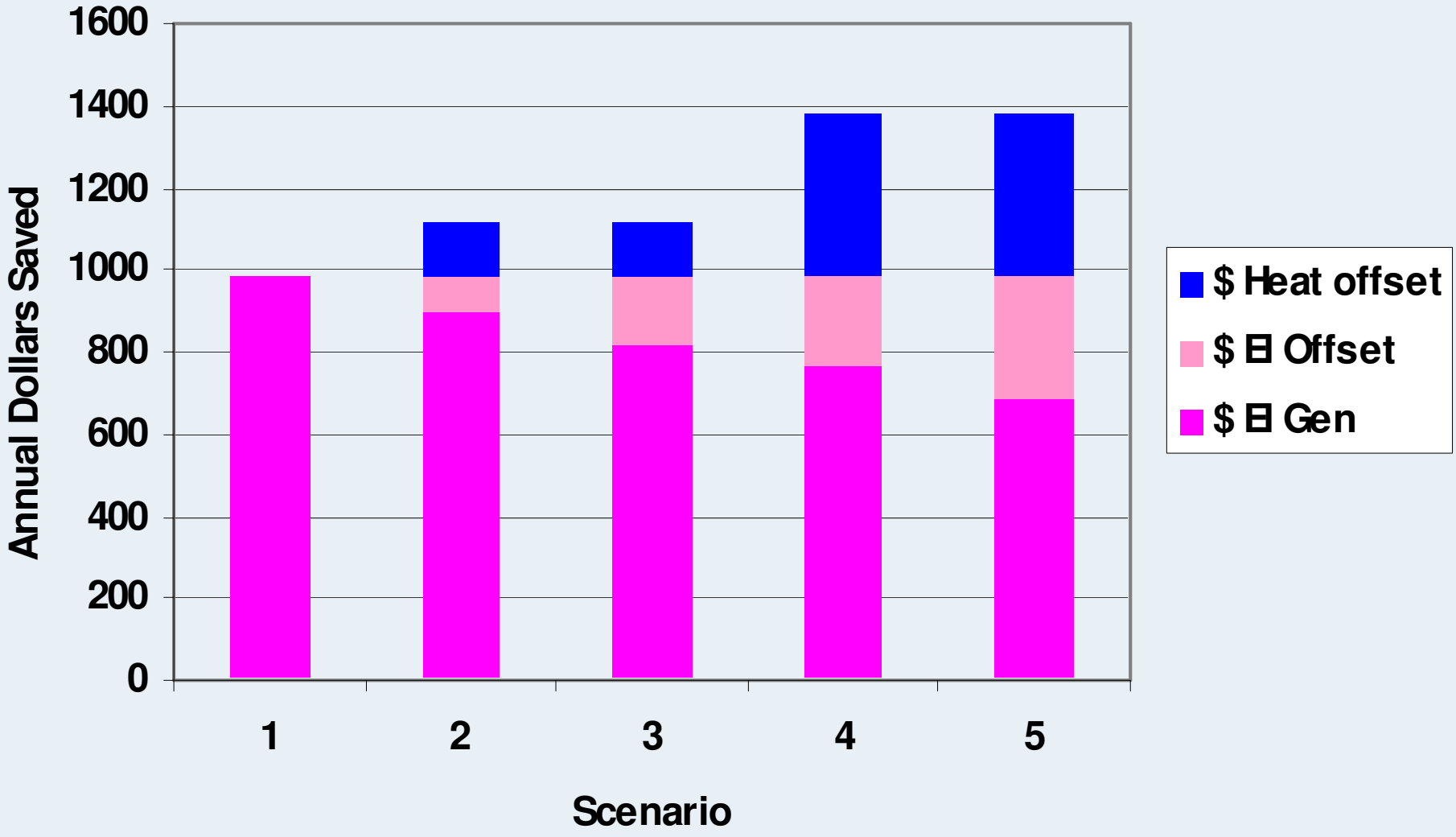
Turning Concepts into Reality

	WaterCHP	WaterEl	EthanolCHP	EthanolEl	R123CHP	R123El
P4 (kPa)	1548	1548	1756	1279	2900	3000
P6 (kPa)	18.9	3.537	44.56	8.755	276.9	97.92
Eta_t	0.65	0.65	0.85	0.85	0.85	0.85
Eta_p	0.85	0.85	0.85	0.85	0.85	0.85
Eff - Elec	0.08	0.096	0.085	0.104	0.087	0.11
Eff - Heat	0.42		0.41		0.39	
E_net (kJ/kg)	397.2	506.1	180.6	241	34.49	50.28
T1(K)	332	300	332	300	332	300
T4(K)	473	473	473	473	473	473
T_amb	290	290	290	290	290	290
Q_in (kJ/kg)	2544	2678	1080	1187	212.2	234
Q_out (kJ/kg)	2103	2116	879.6	919.1	164.3	178.1
Q_regen					44.65	45.79
mdot	0.0074	0.0059	0.0165	0.0122	0.0670	0.0519
Area (m^2)	45	37.6	42.5	34.7	33.8	28.9
Imax (W/m^2)	825	825	825	825	825	825
Eta_sol	0.51	0.51	0.51	0.51	0.51	0.51

Electrical Generation Efficiency

Table A. Solar-thermal-electric Rankine cycle with all working fluids

Annual savings by scenario

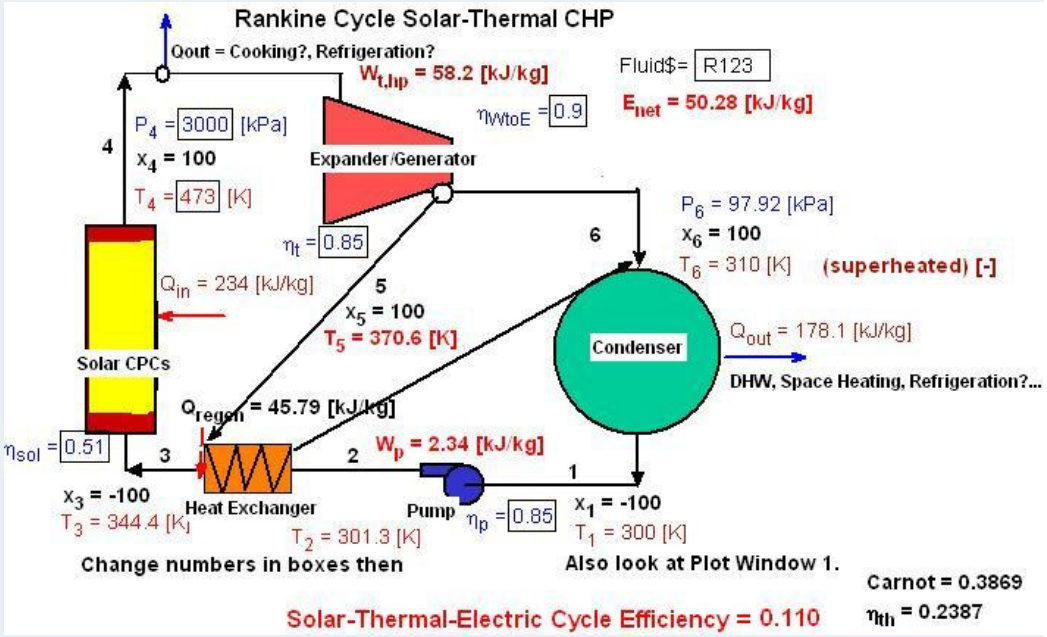


System Analysis Summary

Turning Concepts into Reality

- Technical Design
  - Rankine cycle
  - Working fluids
  - CPC Panels
- Economic Analysis
  - Installed Cost $26,794
  - Cost/kWh $0.31
  - Cost/peak W $4.96
- Use/demand scenarios
  - $950 to $1400 power generation/offset demand
  - 5 implementations considered

Scenario 1 system design



Future Work

Turning Concepts into Reality

Laundry list to do:

- Design of low-temperature expander generator using Energy/Sustainability optimization integrated design process (UCB Mechanical Engineering, D. Dornfeld, C. Reich-Weiser)
- Integration of XCPC collectors with prototype system (UC Merced)
- Further economic analysis of natural gas / electrical offsetting scenarios to motivate DOE, CEC funding proposals

Needs:

- Connections with interested parties at LBL (Applied Helios?)